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STUDIES OF EXTRA-SOLAR OORT CLOUDS AND THE KUIPER DISK

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INTRODUCTION

This is the September 1995 Semi-Annual report for ~~NAGW-3023-(SwRI-Project 15-4971)~~, *Studies of Extra-Solar Oort Clouds and the Kuiper Disk*, (S.A. Stern, PI).

We are conducting research designed to enhance our understanding of the evolution and detectability of comet clouds and disks. This area holds promise for also improving our understanding of outer solar system formation, the bombardment history of the planets, the transport of volatiles and organics from the outer solar system to the inner planets, and to the ultimate fate of comet clouds around the Sun and other stars. According to "standard" theory, both the Kuiper Disk and the Oort Cloud are (at least in part) natural products of the planetary accumulation stage of solar system formation. One expects such assemblages to be a common attribute of other solar systems. Therefore, searches for comet disks and clouds orbiting other stars offer a new method for inferring the presence of planetary systems.

This project consists of two major efforts: (1) observational work to predict and search for the signatures of Oort Clouds and comet disks around other stars; and (2) modelling studies of the formation and evolution of the Kuiper Disk (KD) and similar assemblages that may reside around other stars, including β Pic. These efforts are referred to as Task 1 and 2. The main collaborators with PI Stern in Task 1 are CoIs Drs. David Weintraub (Vanderbilt U.) and Mike Shull (U. Colorado). The main collaborator in Task 2 is CoI Dr. Glen Stewart (U. Colorado).

RECENT PROGRESS

Task 1: Observational Studies of Comet Disks and Clouds

Last year we completed 2 new observing runs at the IRAM and SEST submm telescopes to study one of the best IRAS IR-excess comet cloud candidates, α PsA (Fomalhaut), τ Ceti, β Pic, and HD98800. Our HD98800 measurements were judged of immediate interest and published in an IAU Circular (IAUC 6003; June 1994).

Our observing work will continue in early 1996 with multi-channel bolometer observations of IR excess stars at IRAM and (if approved) a CSO run to survey ~ 15 pulsars for evidence of cold dust emission indicative of planetary formation.

In parallel with our observing program, two papers on theoretical subjects related to comet cloud and planetary detection have been completed, submitted, and published. In the first, PI Stern developed a new method for directly detecting planets. This method is based on the fact that giant impacts, like the one forming the Earth-Moon system, cause the target planet to become IR-luminous for several hundred to several thousand years. The paper demonstrates (i) that such events will be detectable from the twin-Keck interferometer, and (ii) that in a young star cluster like Orion, between one and a few such "hot planets" should be extant at any given time. In the second paper, PI Stern and collaborator Shull have shown that the *lack* of a galactic population of Gamma Ray Bursters (GRBs) constrains the fraction of stars in the galaxy that have Oort Clouds

to $\leq 20\%$. These papers have now appeared in print.

Task 2: Collisional Modelling of the Kuiper Disk

We have now completed the first model of collision rates of the Kuiper Disk. With this model we explored the rate of collisions among bodies in the present-day Kuiper Disk as a function of the total mass and population size structure of the Disk. We find that collisional evolution is an important evolutionary process in the Disk as a whole, and indeed, that it is likely the dominant evolutionary process beyond ≈ 42 AU, where dynamical instability timescales exceed the age of the solar system. Two key findings we report from this modelling work are: (i) That unless the Disk's population structure is sharply truncated for radii smaller than ~ 1 -2 km, collisions between comets and smaller debris are occurring so frequently in the Disk, and with high enough velocities, that the small body (i.e., km-class object) population in the disk has probably developed into a collisional cascade, thereby implying that the Kuiper Disk comets may not all be primordial, and (ii) that the rate of collisions of smaller bodies with larger $100 < R < 400$ km objects (like 1992QB₁ and its cohorts) is so low that there appears to be a dilemma in explaining how QB₁s could have grown by binary accretion in the disk as we know it. Given these findings, it appears that either the present-day paradigm for the formation of Kuiper Disk is failed in some fundamental respect, or that the present-day disk is no longer representative of the ancient structure from which it evolved. In particular, it appears that the 30-50 AU region of the Kuiper Disk has very likely experienced a strong decrease in its surface mass density over time. This in turn suggests the intriguing possibility that the present-day Kuiper Disk evolved through a more erosional stage reminiscent of the disks around the A-stars β Pictoris, α PsA, and α Lyr. These results were published in *The Astronomical Journal* this year.

We have also used this model and a second code to estimate the detectability of IR emission from debris created by collisions. We found that eccentricities in the Kuiper Disk are high enough to promote erosion on virtually all objects up to ~ 30 km, independent of their impact strength. Larger objects, such as the 50-170 km radius "QB₁" population, will suffer net erosion if their orbital eccentricity is greater than ≈ 0.05 (≈ 0.1) if they are structurally weak (strong). The model predicts a net collisional erosion rate from all objects out to 50 AU ranging from 3×10^{16} to 10^{19} g yr⁻¹ depending on the mass, population structure, and mechanical properties of the objects in the Disk. We find two kinds of collisional signatures that this debris should generate. First, there should be a relatively smooth, quasi-steady-state, longitudinally isotropic, far IR (i.e., ~ 60 μ m peak) emission near the ecliptic in the solar system's invariable plane ecliptic, caused by debris created by the ensemble of ancient collisions. The predicted optical depth of this emission could be as low as 7×10^{-8} , but is most likely between 3×10^{-7} and 5×10^{-6} . We find that this signature was most likely below IRAS detection limits, but that it should be detectable by both ISO and SIRTf. Second, very recent impacts in the disk should produce short-lived, discrete clouds with significantly enhanced, localized IR emission signatures superimposed on the smooth, invariable plane emission. These discrete clouds should have angular diameters up to 0.2 deg, and annual

parallaxes up to 2.6 deg. Individual expanding clouds (or trails) should show significant temporal evolution over timescales of a few years. As few as zero or as many as several 10^2 such clouds may be detectable in a complete ecliptic survey at ISO's sensitivity, depending on the population structure of the Kuiper Disk. This work was recently accepted for publication in *Astronomy & Astrophysics*. This paper is attached in preprint form.

These two papers were also accompanied by an invited review, submitted to the *Planetary Ices* book, summarizing the present state of knowledge about the Kuiper Disk and Pluto. Additionally, PI Stern gave three invited talks summarizing the collisional modelling results obtained under the Origins program. A list of these invited talks is attached.

Finally, in July 1995, we organized and sponsored a 2-day workshop on collisions in the Kuiper Disk. This workshop was attended by D. Davis (PSI), P. Farinella (Italy), R. Canup (U. Colorado), M. Festou (France), J. Colwell (U. Colorado), H. Levison (SwRI), and PI Stern (SwRI). The proceedings of this workshop were informally published and distributed among the participants. A copy was also sent to Origins program scientist Trish Rogers.

RELEVANT PUBLICATIONS

The Detectability of Extrasolar Terrestrial and Giant Planets During Their Luminous, Final Accretion. S.A. Stern. *The Astronomical Journal*, **108**, 2312, 1994.

Gamma Ray Bursts Constraints on the Galactic Frequency of Extra-Solar Oort Clouds. J.M. Shull and S.A. Stern. *The Astronomical Journal*, **109**, 690, 1995.

Pluto and the Kuiper Disk. S.A. Stern. Submitted to "Ices in the Solar System." (C. DeBergh, B. Schmitt, M.C. Festou, eds.), 1995.

Collision Rates in the Kuiper Disk and Their Implications. S.A. Stern, *The Astronomical Journal*, **110**, 856, 1995.

Signatures of Collisions in the Kuiper Disk. S.A. Stern. *Astronomy & Astrophysics*, in press, 1995.

RECENT SCIENTIFIC PRESENTATIONS & ABSTRACTS

Collisions in the Kuiper Disk. Astronomy Luncheon Seminar. Queen's University Department of Physics. Kingston, Ontario, 2 February 1995.

Pluto, Charon, and The Kuiper Disk. Ices in the Solar System Meeting. Toulouse, France, 25 March 1995.

The Kuiper Disk: Evidence for Arrested Planetary Accretion? Laboratory for Atmospheric and Space Physics Seminar, University of Colorado, Boulder, CO, 28 September 1995.

Signatures of Collisions in the Kuiper Disk

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02 Tables

07 Figures

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Abstract

We explore the rate of collisionally-produced mass injection in the present-day Kuiper Disk as a function of the total mass and population size structure of the disk. Our objective is to estimate the detectability of IR emission from debris created by collisions. We find that eccentricities in the Kuiper Disk are high enough to promote erosion on virtually all objects up to ~ 30 km, independent of their impact strength. Larger objects, such as the 50-170 km radius “QB₁” population, will suffer net erosion if their orbital eccentricity is greater than ≈ 0.05 (≈ 0.1) if they are structurally weak (strong). Our model predicts a net collisional erosion rate from all objects out to 50 AU ranging from 3×10^{16} to 10^{19} g yr⁻¹, depending on the mass, population structure, and mechanical properties of the objects in the Disk. We find two kinds of collisional signatures that this debris should generate. First, there should be a relatively smooth, quasi-steady-state, longitudinally isotropic, far IR (i.e., $\sim 60\mu\text{m}$ peak) emission near the ecliptic in the solar system’s invariable plane ecliptic, caused by debris created by the ensemble of ancient collisions. The predicted optical depth of this emission could be as low as 7×10^{-8} , but is most likely between 3×10^{-7} and 5×10^{-6} . We find that this signature was most likely below IRAS detection limits, but that it should be detectable by both ISO and SIRTf. Second, very recent impacts in the disk should produce short-lived, discrete clouds with significantly enhanced, localized IR emission signatures superimposed on the smooth, invariable plane emission. These discrete clouds should have angular diameters up to 0.2 deg, and annual parallaxes up to 2.6 degrees. Individual expanding clouds (or trails) should show significant temporal evolution over timescales of a few years. As few as zero or as many as several 10^2 such clouds may be detectable in a complete ecliptic survey at ISO’s sensitivity, depending on the population structure of the Kuiper Disk.

1. Introduction

Almost a half-century ago, Edgeworth (1949) and Kuiper (1951) made prescient predictions that the Sun should be surrounded by a disk-like ensemble of comets and other “debris” located beyond the orbit of Neptune. The case for such a primordial reservoir was strengthened when it was later pointed out that such a disk could be an efficient source region to populate the low-inclination, short-period comets (i.e., the Jupiter Family Comets; Fernández 1980). Convincing dynamical simulations supporting this link between the Jupiter Family comets and the Kuiper Disk (KD) region arose when Duncan, Quinn, & Tremaine (1988) and later Quinn et al. (1990) showed that a low-inclination source region appears to be required for a low-inclination orbit distribution of the Jupiter Family Comets. Figure 1 is a schematic diagram revealing the gross architecture of the this disk in relationship to the orbits of the five known outer planets.

The computational capabilities available to Duncan and coworkers in the mid-1980s required some important approximations be accepted (for reviews of this work, cf., Weissman 1993, and Stern 1995a). Although these compromises were criticized by Bailey & Stagg (1990), Duncan et al.’s work generated interest in the Kuiper Disk by both modellers and observers. Of particular relevance here are the Holman & Wisdom (1993) and Levison & Duncan (1993) studies of orbital evolution in the Disk. These workers found a time-dependent dynamical erosion of the Disk population inside ≈ 42 AU, caused by nonlinear perturbations from the giant planets. The dynamical chaos resulting from these perturbations is ultimately responsible for the transport of short-period comets from the long-lived Kuiper Disk reservoir to planet-crossing orbits where they can be routinely detected. Based on the bias-corrected population of Jupiter Family Comets and the dynamical transport efficiency of comets from the Kuiper Disk to the inner planets region, Duncan, Levison, & Budd (1995) have since estimated that $\sim 10^{10}$ comets orbit in the Disk between 30 and 50 AU from the Sun.

Observational confirmation of the Kuiper Disk was first achieved with the discovery of object 1992QB₁ by Jewitt & Luu (1993). As of late 1995, no fewer than 30 QB₁-like, trans-Neptunian objects have been discovered (Jewitt & Luu 1995; Stern 1995a). These icy outer solar system bodies are expected to have dark surfaces consisting of an icy matrix contaminated by silicates and organics. Assuming a typical (i.e., cometary) geometric albedo of 4%, and the absence of coma, the distances and magnitudes of these objects indicate they have radii between roughly 50 and 180 km. Based on the detection statistics

obtained to date, one can easily estimate that a complete ecliptic survey would reveal $\sim 3.5 \times 10^4$ such bodies orbiting between ≈ 30 and 50 AU. Simple power-law extensions of this population predict a cometary population (which we define as bodies with radii between 1 and 6 km) of $\sim 10^{10}$, which is similar to the dynamical modelling estimates obtained by Duncan et al. (1995) to satisfy the short-period comet flux. Very recently, Cochran et al. (1995a,b) have reported Hubble Space Telescope results giving the first direct evidence for comets in the Kuiper Disk.

The objective of this paper is to examine whether there might be detectable signatures of collisions in the Kuiper Disk. An extensive study of collision rate dependencies in the Kuiper Disk has been published by this author (Stern 1995). We are aware of an unpublished manuscript by Alcock & Hut (1995) on the detectability of individual flashes from comet-comet collisions in the Kuiper Disk, and an abstract by Dasgupta et al. (1994) predicting the small grain population of the Kuiper Disk; the latter has recently been expanded into a short paper by Backman et al. (1995). The study presented here is more extensive than these previous works, and is aimed specifically at predicting signatures the ISO and SIRTf spacecraft might detect.

This paper is organized as follows. In §2, I summarize our previously-published model for estimating the rate of collisions in the Kuiper Disk, on which many of the results presented here are based. In §3, we evaluate whether collisions in the Disk are primarily erosional or accretional, showing that present-day collisions are expected to be erosive, thereby injecting debris into the Kuiper Disk. In §4, I summarize some key results derived from that model. In §5, I estimate the quasi-steady-state debris mass, debris opacity, and IR brightness expected from the disk. In §6, I discuss the characteristics and number of discrete, expanding debris “clouds” produced by individual collisions during the past few years. In both §5 and §6, comparisons to IRAS, ISO, and SIRTf detection capabilities are made. To close, §7 summarizes the various results and describes how the Kuiper Disk debris detection can make important contributions to our understanding of the mass, size structure, and mean random eccentricity of objects in the Disk.

2. The Collision Rate Model

As described more fully in Stern (1995b; hereafter, Paper I), our model for estimating collision rates in the Kuiper Disk begins by defining the Disk in terms of a power law

exponent, α , on the size distribution of objects in the Disk. Defined in this way, the number of objects $dN(r)$ between radius r and $r + dr$ is given by

$$dN(r) = N_0 r^\alpha dr, \quad (1)$$

where N_0 is a normalization constant set by the estimated number of QB₁ objects. We treat this size distribution as a monotonically decreasing series of radius bins. In what follows, we choose bodies in each successive radius bin r to be a factor of 1.6 times larger in size (and equivalently, 4 times higher in mass), ranging from $r = 0.1$ km to $r = 162$ km.

We also define a power law exponent β on the radial distribution of heliocentric surface mass density $\Sigma(R)$ in the disk, so that

$$\Sigma(R) = \Sigma_0 R^\beta, \quad (2)$$

where Σ_0 is the normalization constant. Because there is presently no information on the way in which ensemble-averaged inclinations ($\langle i \rangle$) and eccentricities ($\langle e \rangle$) vary in the Kuiper Disk, we adopt a disk-wide $\langle i \rangle$ and $\langle e \rangle$ for each run, and vary these quantities from run to run as free parameters to explore how sensitive the model results are to these variables.

Once the disk is defined as described above, we bin the disk into a series of concentric tori (at successive semi-major axes a) that are 1 AU in width. For each size bin/heliocentric bin pair, the model computes the collision rate that a target of given size experiences from potential impactors in bins of equal or smaller size. This is of course a function of $\langle ae \rangle$, since $\langle e \rangle$ controls both the internal velocity dispersion in the disk, and $\langle ae \rangle$ controls the degree of heliocentric bin crossing.

To compute collision rates we adopt a particle in a box formalism. This approach states that the instantaneous collision rate c of target bodies with semi-major axis a , eccentricity e , and radius r_x being struck by impactors of radius r_y , is just

$$c(r_x, r_y, a, e) = n \sigma_g v, \quad (3)$$

where n is the local space density of impactor bodies, v is the local average crossing velocity of the target body against the impactor population at distance R , and σ_g is the gravitational-focusing corrected collision cross section of the impactor+target pair.

Gravitational focusing is an important correction for targets in the QB₁ size range and larger, particularly in the case of very low eccentricities (e.g., $\langle e \rangle < 10^{-2}$). The orbit-averaged collision rate $\bar{c}(r_x, r_y, a, e)$ can be written to show all its explicit dependencies in the model as

$$\bar{c}(r_x, r_y, a, e, R) = \sum_{R=a(1-\langle e \rangle)}^{a(1+\langle e \rangle)} f(a, \langle e \rangle, R) n(r_y, R) v_{xy}(a, \langle e \rangle, \langle i \rangle, R) \sigma_g(r_x, r_y, v_{xy}, v_{esc}(x+y)), \quad (4)$$

where the term f represents the ratio of the time the target body in an orbit defined by $(a, \langle e \rangle, \langle i \rangle)$ spends in each torus it crosses during its orbit ($T(a, \langle e \rangle, R)$), to the target body's orbital period, $\sqrt{\frac{4\pi^2 a^3}{GM_\odot}}$.

To compute $T(a, \langle e \rangle, R)$ we solve the central-field, Kepler time of flight equation explicitly for every $(a, \langle e \rangle)$ pair in the run's parameter space. The number density of impactors $n(r_y, R)$ in the torus centered at distance R is computed from the mass of the Disk, the Disk's wedge angle $\langle i \rangle$, its heliocentric surface density power-law, and the Disk's population size structure power law. The collision timescale $\tau(r_x, r_y, a, e)$ is just $\bar{c}^{-1}(r_x, r_y, a, e)$.

The code which implements this model produces an array containing collision rates $\bar{c}(r_x, r_y, a, e)$ throughout the specified disk, where the free parameters defining the disk are the total number of QB₁'s, α , β , and $\langle e \rangle$. We assume $\langle i \rangle = \frac{1}{2}\langle e \rangle$.

3. Are Kuiper Disk Collisions Predominately Accretional or Erosional Today?

Before continuing, it is relevant to ask whether collisions in the Kuiper Disk are energetic enough to primarily promote erosion, or alternatively, sufficiently gentle to promote growth.

Whether a collision between an impactor and a target results in growth or erosion depends primarily on the energy of the impact and the mass and strength of the target. In the Kuiper Disk, the typical approach velocity of two objects at a distance large compared to the Hill sphere of the target can be reasonably-well approximated by

$$v_\infty = \sqrt{2}v_K (\langle e^2 \rangle + \langle i^2 \rangle)^{\frac{1}{2}}, \quad (5)$$

where v_K is the local Keplerian velocity. For $\langle i \rangle = \frac{1}{2}\langle e \rangle$ we have

$$v_\infty = \sqrt{3}\langle e^2 \rangle^{\frac{1}{2}}v_K. \quad (6)$$

The energy at impact is therefore given by

$$\frac{1}{2}\mu v_{imp}^2 = \frac{1}{2}\mu \left(v_{esc} + \sqrt{3}\langle e^2 \rangle^{\frac{1}{2}} v_k \right)^2, \quad (7)$$

where μ is the reduced mass and v_{esc} is the escape velocity of the two colliding bodies measured at the radius of impact. The critical velocity for erosion to occur is given approximately by the requirement that the specific impact energy must exceed the total energy required to break up the surface and then disperse the ejecta out of the gravitational well of the impactor/target collision pair. The impact energy, E_{imp} , as given by Eqn (7), must equal or exceed these energy sinks. The critical condition for the target to lose mass is that the mass of the ejecta exceeds the mass of the impactor. Therefore, if the impactor mass is small compared to the target, then one requires

$$\frac{1}{2}v_{imp}^2 > \kappa \left(v_s^2 + \frac{1}{2}v_{esc}^2 \right), \quad (8)$$

where v_s represents the velocity required to mechanically shatter the target surface, v_{esc} represents the velocity required to disperse the debris to infinity, and κ is a factor that takes into account energy partitioned into heat, sublimation, hydrodynamic effects, and other factors. In what follows we assume $\kappa = 8$ or 10 (cf., Davis et al. 1989). Now we take the specific energy for mechanical breakup of the target to be

$$v_s^2 = s, \quad (9)$$

where s is the specific strength of the target material at zero compression. Of course,

$$v_{esc} = \sqrt{\frac{2GM_t}{r_t}}, \quad (10)$$

where G is the universal gravitational constant, M_t is the combined mass of the target and impactor, and r_t is the combined radii of these two objects. Therefore, from Eqns (7)-(10) one can derive the condition which we must solve for e^* , the critical eccentricity at which impact energies are high enough to promote net erosion:

$$v_{esc}^2 + 2\sqrt{3}e^* v_K v_{esc} + 3(e^*)^2 v_K^2 - \kappa v_s^2 - \kappa v_{ej}^2 = 0, \quad (11)$$

Notice e^* is a function of several target parameters, including the strength, size, and mass.

Table 1 solves Equation (11) solutions for the critical erosion eccentricity e^* , both for impacts onto strong (e.g., rock/ice) targets ($\rho = 2 \text{ g cm}^{-3}$ and $s = 3 \times 10^6 \text{ erg g}^{-1}$), and relatively weak (e.g., snow-like) targets ($\rho = 0.5 \text{ g cm}^{-3}$ and $s = 3 \times 10^4 \text{ erg g}^{-1}$; these may be more applicable to comets in the Disk, cf., Ásphaug & Benz 1994); results are shown at heliocentric distances of 35 and 60 AU. Following the results discussed in Fujiwara et al. (1989), we assume $v_{ej} = 0.2v_{imp}$.

The results presented in Table 1 can be summarized as follows. For targets with radii smaller than $\approx 30 \text{ km}$, $e^* < 0.01$, independent of heliocentric distance and the strength of the target surface (within our parameter space). For reference, at 40 AU an $\langle e \rangle = 0.01$ corresponds to a typical encounter velocity at infinity of 82 m/s. Since all objects with measured eccentricities in the Disk have eccentricities in excess of 0.01 (Jewitt & Luu 1995; H.F. Levison, pers. comm. 1995), we conclude that most objects of radius a few tens of kilometers or less in the Disk are likely to be eroded when they suffer a collision. These results remain valid even if the characteristic ejecta velocity is as low as 5% of the impact speeds instead of the 20% used in Table 1.

For QB₁-sized targets with radii near 100 km, we find $e^* \geq 0.02 - 0.03$ are required for net erosion if they are weak, and $e^* \geq 0.05 - 0.06$ is required if they are strong. Similarly, for QB₁-like objects with $R=170 \text{ km}$, which is comparable to the largest-discovered objects in the Disk to date, $e^* \geq 0.04 - 0.05$ is required if the objects are weak and $e^* \geq 0.09 - 0.10$ is required to result in net erosion if the objects are strong. Interestingly, it is also worthwhile to note that if the characteristic ejecta velocity is as low as a few percent of the impact speeds, then e^* will rise dramatically and the QB₁ population will be in an accretional regime, even for eccentricities as high as 0.2–0.5. We thus find that some QB₁'s should be undergoing erosion, while others may be in an accretional regime, depending on their eccentricity and strength. However, until much better eccentricity statistics become available, it is not possible to determine if the QB₁ population as a whole is gaining or losing mass. All we can say is that the range of detected eccentricities span the range of e^* 's, creating a complex situation.

In summary, small objects like comets are being eroded when collisions occur on them in the Kuiper Disk, but whether larger objects like the QB₁'s suffer erosion or accretion depends on their surface strength and the relative eccentricity of the impactor/target pair. Regardless of the net fate of the QB₁ population, collisions inject collisional debris into

the present-day Disk.

4. Collision Rates in the Present-Day Kuiper Disk

In Paper I, an extensive set of collision rate calculations were presented. Here, we briefly summarize some results obtained from those calculations as a prelude to the calculation of observable parameters arising from those collisions.

In the work presented in Paper I and what follows below, it is assumed that the Kuiper Disk has an inner radius of 35 AU and an outer radius of 70 AU. We let eccentricity range as a free parameter from 2×10^{-4} to 2×10^{-1} , which extends over a range of eccentricities considerably greater than actually seen in the Kuiper Disk objects detected to date. As noted before, we assume $\langle i \rangle = \frac{1}{2} \langle e \rangle$.

Four cases defining the heliocentric mass dependence and size distribution of objects in the Disk will be presented here. These four cases represent the combinations of two size distributions of objects (cf., α in Eqn. 1) and two heliocentric mass distributions (cf., β in Eqn. 2).

Our favored size distribution, which we call the nominal (NOM) case, connects the observationally-estimated $\sim 3.5 \times 10^4$ QB₁-sized objects (Jewitt & Luu 1995) inside 50 AU with the modelling-derived estimates of $\sim 10^{10}$ comets (Duncan et al. 1995) in a single power law with $\alpha = -11/3$. Our second case assumes $\alpha = -4$, which gives a Constant Mass (CM) in every logarithmic size bin. Relative to the NOM case which produces $\approx 10^{10}$ for 35,000 QB₁'s (100 km in radius or larger), the CM case produces $\approx 5 \times 10^{10}$ comets.

For the heliocentric distribution of mass in the Disk, the two cases we run are defined as follows. One case assumes a Constant Mass per Heliocentric Bin (CMHB; $\beta = -1$), which corresponds to a surface mass density that declines with heliocentric distance as R^{-1} . The second, and more realistic case, assumes a Declining Mass per Heliocentric Bin (DMHB; $\beta = -2$), corresponding to a surface mass density falling like R^{-2} . These two cases bracket a realistic range of parameter space (Lissauer 1987).

Table 2 summarizes these four run cases (and a fifth case we shall discuss later). We now present some key results. Figure 2 depicts collision timescale results obtained at 40 and 60 AU for the NOM/DMHB case. The upper panels show the collision timescale for $\langle e \rangle \approx 10^{-2}$. The lower panels show the collision timescale for $\langle e \rangle \approx 10^{-1}$. These values of $\langle e \rangle$ are representative of measured eccentricities in the Kuiper Disk (cf., Stern 1995a;

Jewitt & Luu 1995). Figure 3 depicts the same kind of data for the CM/DMHB case. The reader is referred to Paper I to see the collision calculations for the CMHB cases.

As discussed in detail in Paper I, the key results obtained from the collision model are: (i) That unless the Disk’s population structure is sharply truncated below ~ 1 km, comet-comet collisions are occurring so frequently, and with high enough velocities, that the primordial cometary population would be significantly depleted over the age of the solar system. (ii) That the rate of collisions of smaller bodies with QB₁-size (i.e., $100 < R < 600$ km) objects is so low today that there appears to be a dilemma in explaining how QB₁’s could have grown by binary accretion in the Disk as we know it. And (iii) that collisional evolution is important not only at the inner edge of the Disk near 40 AU, but also much farther out, at 60 AU, if the Disk extends that far. These findings suggest that collisional evolution plays an important role throughout the Kuiper Disk, and that collisions play a dominant role beginning near 42 AU, where dynamical timescales exceed the age of the solar system. Because collisions in the Disk are modifying the size distribution, these findings also argue that the population structure of the present-day Disk appears to be in disequilibrium. We refer the reader to Paper I for a more complete discussion of these aspects of collisional evolution in the Kuiper Disk, and now turn to the primary subject of this report—the observable signatures created by collisions in the Disk.

5. The Smooth Ecliptic Signature

As described above, we have found that typical collisions taking place today among small bodies in the Kuiper Disk are erosive. It is well known from studies of the asteroid belt that such collisions produce a power-law distribution of debris ranging from a largest fragment of radius scale a significant fraction of the target size, down to fine dust (e.g., Holesapple 1993). Our interest is in computing the optical depth and thermal emission brightness of the debris. In what follows we study the collisionally-generated debris tail of objects down to sizes as small as $3 \mu\text{m}$.

We begin by first estimating the steady-state amount of debris in the Kuiper Disk, which we compute according to

$$M_d(a) \approx \dot{M}(a) T_{loss}(a), \quad (12)$$

where $\dot{M}$ is the time-averaged rate of debris production in the disk, and T_{loss} is the loss

timescale for such debris. The relevant loss processes are dynamical transport owing to perturbations by the giant planets, dynamical loss to Poynting-Roberson (P-R) drag, and physical loss to collisions which destroy grains. Radiation pressure is not as effective as P-R drag for particles several microns in size and larger (e.g., Burns et al. 1979), so we neglect its effects in the scaling calculations that follow. We also neglect particle sublimation, because H₂O/silicate grains and larger particles in our size range beyond ≈ 15 AU have sublimation lifetimes longer than the age of the solar system.

In our model we take $T_{loss}^{-1} = T_{dyn}^{-1} + T_{pr}^{-1} + T_{dc}^{-1}$, where T_{dyn} is the dynamical loss time for objects suffering perturbations by the giant planets, T_{pr} is the Poynting-Roberson timescale for dust and small particles, and T_{dc} is the collisional fragmentation timescale for self-collisions among debris and debris collisions with larger objects, where “debris” particles are all objects smaller than 0.1 km, down to a 3 μm lower size limit. The T_{dyn} data were kindly supplied by H. Levison.

We compute $\dot{M}(a)$ by summing the ejected mass over all target-impactor collisions. We determine the mass ejected by a given impactor striking a target at velocity v_{imp} by balancing the energy budget of the impact against energy losses to mechanical shattering, and escape from the collision-pair’s potential well. We determine the excess velocity of the escaping mass following previously published results (cf., Fujiwara et al. 1989); the characteristic ejecta velocities we employ are in the range $0.05v_{imp}$ to $0.20v_{imp}$. We assume that only 10% of the energy of the impact is partitioned into the kinetic energy of the debris. This approach is similar to that described in Eqns (7)–(10), but instead of solving for e^* , we solve for the ejected mass m_{ej} at a specified impact velocity defined by the assumed eccentricity of the population and the mutual escape speed of the target+impactor pair. The code caps the maximum ejected mass to be the combined mass of the impactor+target pair. The mass ejected in this way is assumed to follow a standard debris fragmentation power law from a largest fragment down to fine dust a few microns in size (e.g., Holsapple 1993).

We compute the Poynting-Roberson (P-R) drag timescale for a dust particle according to

$$T_{pr} = 7 \times 10^6 r_p \rho_p (a_2^2 - a_1^2) (1 - e) \text{ years}, \quad (13)$$

(e.g., Gustafson 1994), where r_p is the particle radius in cm, ρ_p is the particle density in g cm^{-3} , a_1 is the particle’s initial semi-major axis in AU, and a_2 is the particle’s final

radius in AU; in what follows we take $a_2 = 30$ AU, where we assume Neptune's dynamical influence spatially truncates the Kuiper Disk debris distribution. Equation (13) implies a characteristic P-R loss timescale of 5×10^6 years for a 10-micron ice particle with unit density at 40 AU; at 60 AU the timescale for such a particle is near 2×10^7 years.

Now consider the debris collision timescale, T_{dc} . This is the timescale for debris particles to be lost to collisions with one another or by striking a large Kuiper Disk object. We compute T_{dc} using the same particle in a box formalism as described in §3, with the number density of debris particles calculated from the $\dot{M}(a)$ and the assumption that the population $N(a) \sim a^{-3.5}$.

During the time interval between their creation and their loss, particles created by collisions will experience azimuthal smoothing due to regression of their arguments of perihelion, regression of their orbit nodes, as well as Keplerian shear resulting from post-collision velocity dispersion, radiation pressure, and differential P-R drag. As it turns out, the Kepler shear time for orbits 1 AU apart to separate by 180 deg is very short ($\sim 10^4$ years) compared to both the nodal regression timescales (each $\sim 10^7$ years) and the PR drag timescale ($\sim 6 \times 10^5$ years). As a result, we predict the development of a longitudinally-smoothed, quasi-steady-state distribution of collisional debris to develop.

$\dot{M}$ calculations performed using the model run results shown in Figures 2 and 3 predict time-averaged debris production rates in the range $\approx 3 \times 10^{16}$ to 10^{19} g yr $^{-1}$ in the Kuiper Disk, depending on the characteristic ejecta speed relative to the impact velocity. Given this rate of production and the T_{loss} timescales discussed above, one sees that the Kuiper Disk should contain many comet masses of fine debris at any time.

Once $\dot{M}(a)$ and $T_{loss}(a)$ are calculated for a given run case as a function of debris size, we can estimate the disk's quasi-steady state geometric radial optical depth at a specified wavelength λ in debris of radius r_p at heliocentric distance a as

$$\tau(a, \lambda, r_p) = \frac{A_d(a, \lambda, r_p)}{A_{tot}(a)}, \quad (14)$$

where A_d is the integrated area of all the collision products in the heliocentric bin at distance a , and A_{tot} is the total projected area of the Kuiper Disk on the sky, which we take as $4\pi a^2 \sin i$. A_d is computed according to

$$A_d(a, \lambda, r_p) = N_d(a, r_p) \pi r_p^2 \eta(\lambda, r_p), \quad (15)$$

where $N_d(a, r_p)$ is the number of debris particles of size r_p at distance a and $\eta(\lambda, r_p)$ is the optical correction factor for particle cross sections used when $r_p \leq \lambda$. We adopt $\eta(\lambda) = 1$ unless $r_p \leq \lambda$, in which case we take

$$\eta(\lambda) = \left(\frac{r_p}{\lambda}\right)^{2.0}. \quad (16)$$

To obtain a total optical depth $\tau(\lambda)$, we numerically integrate $\tau(a, \lambda)$ over r_p and a , with $N_d(a, r_p)$ provided from the model described here and in §2 and §3.

Figures 4a and 4b present optical depth estimates calculated in this way for the two collision runs presented in Figures 2 and 3, with an assumed IR observation wavelength of $\lambda = 60 \mu\text{m}$. These optical depth estimates are presented as a function of $\langle e \rangle$, ρ , and s . Panel 4c presents the same calculation for a Kuiper Disk population that is truncated below radii of 1 km, as suggested in Paper I (the details of this population are given as the final case described in Table 2). Because the population of colliding bodies is so sharply reduced in the panel c case, panel c likely gives a lower limit to the $60 \mu\text{m}$ optical depth of the Kuiper Disk.

On examining the curves in Figure 4, one sees there are three regimes in each plot. The first (i.e., leftmost) regime, which is described by the straight-line decrease in $\tau(e)$ for $\langle e \rangle < e^*$, is simply the optical depth of the macroscopic (i.e., 0.1–200 km radius) Kuiper Disk population. The optical depth decreases with $\langle e \rangle$ in this regime, primarily because $\langle i \rangle = \frac{1}{2}\langle e \rangle$. As a result, the area of the disk on the sky increases, and the optical depth is diluted. The second (i.e., middle) regime in Figure 4 begins when $\langle e \rangle = e^*$. Once this condition obtains, τ jumps up, since debris generation introduces a new source of optical depth. Notice the location of this jump depends on the strength of the surface of the KD objects. After the τ jump near e^* , a third regime obtains, where τ again declines owing to the dilution effect of increasing the disk eccentricity, as described above.

The main conclusion we draw from Figures 4a and 4b is that the expected IR optical depth for a population with characteristic $0.01 < \langle e \rangle < 0.1$ will likely be in the range 3×10^{-7} to 10^{-5} , but could be as low as 7×10^{-8} . Although we will adopt the range 3×10^{-7} to 3×10^{-5} as a typical steady-state optical depth in the Kuiper Disk, it is worth noting that catastrophic, erosive collisions on large QB₁ objects may occur every $\sim 3 \times 10^7$ years (Stern 1995b). When such collisions occur, the debris mass and optical depth in the Disk can further increase by a factor of 50 or more for a timescale comparable to T_{loss} .

The predicted range of typical-state Kuiper Disk optical depths are higher than the value of 10^{-8} detected in the Solar System's most prominent asteroidal dust bands (Low et al. 1984), but are 10–2000 times lower than the IR optical depths of the disk ensembles around Vega and many other well-known IR-excess A stars (Backman & Paresce 1993).

Is this debris detectable? Figure 5 presents estimates of the debris brightness for three temperatures that span the 40 to 60 K temperatures expected of large grains in simple radiative equilibrium at distances of 35 to 60 AU from the Sun. (We note that small grains can become hotter than 60 K if they are inside 40 AU, but their loss timescale to P-R drag is so short that they do not contribute much optical depth, and therefore do not much affect the assumption of a characteristic emission temperature between 40 and 60 K). Since the actual distribution of temperatures depends on several unknowns, including the grain-size histogram, grain emissivities and albedo, and the heliocentric distribution of grains, we choose to present flux density curves for isothermal ensembles at 40 K, 50 K, and 60 K; given the level of uncertainty in grain parameters at this time, we believe this is preferable to integrating through some arbitrary heliocentric temperature profile. The calculations presented in Figures 5a and 5b assume optical depths of $\tau = 3 \times 10^{-7}$ and $\tau = 3 \times 10^{-6}$, respectively. Superimposed on the debris black-body curves are reference detection limits expected obtainable with IRAS, ISO/ISOPHOT, and SIRTf (cf., Cruikshank et al. 1990; Werner et al. 1991; Backman et al. 1995 have examined the detectability of Kuiper Disk debris by COBE).

Figure 5 indicates that IRAS could have marginally detected the Kuiper Disk if the debris is 50 K or warmer and exhibits $\tau > 10^{-6}$ near 60 μm . Now notice in Figure 4 that if $\langle e \rangle < 10^{-2}$, then optical depths as high as 10^{-5} could obtain. If this were the case, then IRAS would have easily detected the Disk. Since no clear detection has been reported, despite searches (cf., Backman & Paresce 1993), we conclude that IRAS provides indirect evidence that $\langle e \rangle > 10^{-2}$. Additionally, however, it is possible that IRAS could have made a weak detection of the disk if $\langle e \rangle \approx 10^{-2}$. In this regard, the intriguing report of cool, ~ 50 K “zodiacal” dust bands detected in IRAS data (Rowan-Robinson et al. 1991) warrants further analysis.

Concerning ISO and SIRTf, calculations, which are in agreement with those subsequently produced by Backman et al. (1995) indicate that both ISO and SIRTf should be capable of detecting the Kuiper Disk debris background at any plausible temperature (note: if higher temperatures than 60 K obtain for some fraction of the Kuiper Disk debris,

then the emission brightness will be higher, strengthening this conclusion). Kuiper Disk collisional debris should be concentrated in a band perhaps 10-20 degrees in width, centered on the ecliptic (or more accurately, the invariable plane). This emission from smooth Kuiper Disk debris should be distinguishable from zodiacal emission through its (i) narrower latitudinal distribution on the ecliptic, and (ii) ~ 5 times cooler color temperature of 40 to 60 K. If this emission signature is detected with ISO or SIRTf, it will provide a powerful diagnostic for studies of collision rates, and by inference, both the heliocentric mass and population size structure of the Disk.

6. Discrete Signatures from Recent Kuiper Disk Collisions

In addition to the smooth distribution of debris and IR emission resulting from collisional debris in the Kuiper Disk, one also expects there may be small, discrete collision “clouds” generated by recent impacts which have not yet faded into the debris background. Given the low-inclination nature of most orbits in the Kuiper Disk, such clouds will most likely appear as small expanding debris trails, with their major axis preferentially aligned along the invariable plane.

We have constructed a first-order model to evaluate the number of collision clouds that should be detectable. To be conservative, we have assumed that for a cloud to be detectable, it must persist with an optical depth ten times that of the Kuiper Disk background (cf., §5), and with a $\lambda = 60 \mu\text{m}$ size scale larger than an ISO/ISOPHOT angular resolution element (0.8 arcmin) for at least 1 year.

When a given target body such as a comet loses mass in a collision, the debris created by the impact will locally enhance the optical depth of the Kuiper Disk. The emission flux from such an expanding cloud will peak when the cloud’s optical depth, τ_{cl} , reaches unity. The optical depth evolution of the debris cloud can be approximated, for heuristic purposes, by assuming the cloud is spherically expanding. The time at which such a cloud reaches any specified τ_{cl} is given by

$$T(\tau_{cl}) = \sqrt{\frac{3M_{cl}}{4\rho_p r_p v_{ej}^2 \tau_{cl}}}, \quad (17)$$

where M_{cl} is the debris mass in the cloud, r_p and ρ_p are the characteristic debris particle size and density, and v_{ej} is the characteristic expansion velocity of the cloud. As a relevant

example, the time at which a cloud of mass equal to a 2.5 km radius comet reaches unit optical depth is

$$T(\tau_{cl}) \approx 81 \left(\frac{\rho_d}{1 \text{ g cm}^{-3}} \right)^{-1/2} \left(\frac{r_p}{10 \text{ microns}} \right)^{-1/2} \left(\frac{v_{ej}}{5 \times 10^3 \text{ cm s}^{-1}} \right)^{-1} \text{ days.} \quad (18)$$

The radius of the expanding cloud at this time will be

$$R_{cl} = 7 \times 10^9 \left(\frac{\rho_d}{1 \text{ g cm}^{-3}} \right)^{-1/2} \left(\frac{r_p}{10 \text{ microns}} \right)^{-1/2} \text{ cm,} \quad (19)$$

which is about the radius of Jupiter. Such a cloud at a heliocentric distance of 45 AU will have an apparent diameter of ≈ 4 arcsec on the sky and will exhibit an annual parallax of ~ 2.6 degrees.

Of course, one need not detect Kuiper Disk collision clouds at $\tau_{cl} = 1$. In principle, the clouds can be detected against the smoothed Kuiper Disk signal whenever their contrast relative to the background is sufficient. In what follows I assume a background optical depth of 10^{-6} and a cloud:background contrast ratio of 10:1, so that we require $\tau_{cl} = 10^{-5}$. This gives an expansion timescale of:

$$T(\tau_{cl}) \approx 12 \left(\frac{\rho_d}{1 \text{ g cm}^{-3}} \right)^{-1/2} \left(\frac{r_p}{10 \text{ microns}} \right)^{-1/2} \left(\frac{v_{ej}}{10^3 \text{ cm s}^{-1}} \right)^{-1} \text{ years,} \quad (20)$$

with a corresponding radius of

$$R_{cl} = 2 \times 10^{12} \left(\frac{\rho_d}{1 \text{ g cm}^{-3}} \right)^{-1/2} \left(\frac{r_p}{10 \text{ microns}} \right)^{-1/2} \text{ cm,} \quad (21)$$

or 0.15 AU. At 45 AU, such a cloud would have an apparent diameter of ≈ 11 arcmin on the sky.

To improve on these crude scaling calculations, a model has been constructed that uses the collision rate estimates described in §4 as its input. For every collision, the model calculates the amount of mass ejected, after accounting for energy losses to mechanical shattering and escape from the gravity well (cf., Eqns (5)–(11)). Using (i) the ejected mass, (ii) a debris population ranging upward from 3 μm in size to the largest fragments predicted by each collision pair at the specified $\langle e \rangle$, and (iii) adopting a collision debris

power law like $N_d(r_p) \sim r_p^{-3.5} dr_p$ (Davis et al. 1989), the model calculates the spreading time to reach a critical $\tau_{cl} = \zeta \tau$, where ζ is the cloud:sky contrast factor and τ is the Kuiper Disk background optical depth computed for the same collision rate data. Given the collision rate statistics and spreading times to reach τ_{cl} , the model then computes the number of clouds expected on the sky. The free key parameters in this model are $\langle e \rangle$, v_{ej} , and the target's s and ρ . As before, in agreement with past energy partitioning results in catastrophic collisions (e.g., Fujiwara et al. 1989), we vary v_{ej} between 5×10^{-2} and 2×10^{-1} of the impact speed. As usual, we calculate results for two kinds of target bodies—strong (ice/rock) targets and weak (snow-like) targets.

Figure 6 shows the results of such a model calculation using the data in Figure 2 as an input, and the assumptions of a $\lambda = 60\mu\text{m}$ background optical depth of $\tau = 10^{-6}$. Panel *a* shows the number of collision clouds expected from catastrophic collisions on all comets between 1 and 6 km in radius assuming $v_{ej} = 0.20v_{imp}$; panel *b* shows the same for $v_{ej} = 0.05v_{imp}$. Notice: owing to the fact that at lower ejecta velocities a given ejecta energy creates more ejecta, the number of clouds increases as the ratio of v_{ej} to v_{imp} decreases. Notice also that the number of clouds falls with increasing $\langle e \rangle$, which is in part due to the decreasing cloud lifetime with increasing v_{imp} (and therefore increasing v_{ej}).

Recall that all of the QB₁'s with known orbits have $e > 10^{-2}$. For such a population the data in Figure 6 predict that the Disk population structure which produces the collisional timescales shown in Figure 2 should exhibit one or less clouds if the characteristic $v_{ej} \sim 0.2v_{imp}$. However if $v_{ej} \sim 0.05$, then this Disk population structure should produce a few to perhaps 10 to 50 detectable clouds scattered around the ecliptic, depending on the strength of the bodies suffering collisions.

Figure 7 shows the results of the same model run, using the Disk population structure used to produce the collision timescales shown in Figure 3 as an input. For this case the collision rates are higher, in turn producing an order of magnitude more discrete clouds than in the corresponding case shown in Figure 6. As such, this simulation predicts that perhaps as many as 5 recently-created, detectable collision clouds may be scattered around the ecliptic if $v_{ej} \sim 0.20v_{imp}$, and 30 to 300 clouds if $v_{ej} \sim 0.05v_{imp}$!

In closing it is worth noting that although the discrete cloud population model data shown in Figures 6 and 7 assume $\zeta = 10$, it may be that clouds can be detected at much lower contrasts, and then verified via their annual parallax. Setting the contrast criteria to $\zeta = 2$ and retaining the conservative assumption that the background optical depth is

$\tau = 10^{-6}$, increases the estimate of detectable clouds by a factor of just over 2.

7. Summary

As described in Paper I, collisional evolution is an important process in the Kuiper Disk. We have shown that the mean random velocities in the Disk today (as deduced from orbital eccentricities of recently discovered QB₁ objects) strongly suggest that present-day collisions in the Disk are erosive for virtually all objects with radii < 100 km, and for those 100-170 km QB₁ objects with eccentricities in excess of ~ 0.05 if they are weak or ~ 0.01 if they are strong. We predict a time-averaged rate of between 3×10^{16} and 10^{19} g yr⁻¹ of collisional debris, ranging from multi-kilometer blocks to fine dust is being injected into the Disk. Further, we have found that the grinding of objects in the Kuiper Disk produces a population of small particles that dominates the optical depth and therefore the thermal emission from the Kuiper Disk.

This paper has identified two types of detectable IR signatures resulting from Kuiper Disk collisions. First, as described in §5, the Kuiper Disk should produce a longitudinally smoothed, quasi-steady-state population of debris in the solar system's invariable plane. We found that the non-detection of a strong signature of this kind by IRAS indicates that the optical depth of this dust at $60 \mu\text{m}$ is probably $< 3 \times 10^{-6}$. This in turn implies a collisional environment in which $\langle e \rangle > 0.01$ inside at least ~ 50 AU. For the $\langle e \rangle$ range of 0.01 to 0.10 indicated by existing orbit statistics, we predict that the Disk out 50 AU produces a total optical depth of $3 \times 10^{-7} - 5 \times 10^{-6}$ and an IR brightness of 0.2 to 5 MJy/sr at wavelengths between 50 and $100 \mu\text{m}$. These results are in agreement with the findings of less extensive model calculations described by Backman et al. (1995). The Kuiper Disk IR signal should be detectable by ISO. However, if the KD population is strongly truncated below size scales of ~ 1 km, then collisions will be less frequent and we expect optical depths as low as 7×10^{-8} may obtain; this value of τ corresponds to an IR brightness of 0.07 MJy/sr, which is close to, but still probably above ISO's detection limits. In either case the thermal emission from the Kuiper Disk will be dominated by color temperatures in the range 40 to 60 K.

In addition to the smoothed ecliptic signature, recent collisions which significantly erode comets and larger bodies should superimpose local optical depth and therefore IR brightness fluctuations on the smooth Kuiper Disk IR background described above. These

discrete clouds should have brightness temperatures that are much colder than the zodiacal dust, and like the KD ecliptic background. Such clouds should also appear as expanding spherical clouds or elliptical trails with their major axis preferentially oriented along the invariable plane. Before they fade below a 10:1 cloud:background contrast ratio, these clouds should grow to angular scales of many arc minutes, and should display an annual parallax of 1 to 2 degrees, depending upon their distance. The timescale for a given collision cloud to expand and dilute its optical depth below a 10:1 contrast ratio is of order many years, so a sample of many clouds would display a range of sizes and local brightnesses.

The number of such clouds depends strongly on the population of kilometer and sub-kilometer sized objects, the mechanical strength of these bodies, and the mean random eccentricity of this population. Our estimates of the population of such discrete clouds with a brightness 10 times that of the smooth ecliptic signal range from < 1 up to $> 10^2$. This range of uncertainty is in turn due to uncertainties in the population structure and mechanical properties of the Kuiper Disk population. The clear implication of this result is that the surface density of detected clouds on the sky can be used as a probe of these otherwise difficult to ascertain properties of the Kuiper Disk population.

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Table 1: Critical Eccentricities (e^*) for Erosion

Target Radius	35 AU (Strong)	60 AU (Strong)	35 AU (Weak)	60 AU (Weak)
001 km	7×10^{-3}	9×10^{-3}	1×10^{-3}	1×10^{-3}
010 km	6×10^{-3}	7×10^{-3}	2×10^{-3}	3×10^{-3}
100 km	5×10^{-2}	6×10^{-2}	2×10^{-2}	3×10^{-2}
170 km	9×10^{-2}	1×10^{-1}	4×10^{-2}	5×10^{-2}

Notes: Strong target implies $\rho = 2 \text{ g cm}^{-3}$ and $s = 3 \times 10^6 \text{ erg g}^{-1}$; weak target implies $\rho = 0.5 \text{ g cm}^{-3}$ and $s = 3 \times 10^4 \text{ erg g}^{-1}$. In both cases we take $\kappa = 8$ and $v_{\text{ej}} = 0.20v_{\text{esc}}$; see §3 for additional details.

Table 2: Collision Run Cases

Model	M_{disk}	Population	Disk	N_{QB1s}	N_{comets}
	30 AU < R < 50 AU	Type	Type	30 AU < R < 50 AU	30 AU < R < 50 AU
CSD 1e4 25	0.12 $M_{\oplus}$	NOM	DMHB	27,740	7×10^9
CSD 1e4 23	0.32 $M_{\oplus}$	CM	DMHB	31,316	3×10^{10}
CSD 1e4 13	0.42 $M_{\oplus}$	CM	CMHB	41,162	5×10^{10}
CSD 1e4 15	0.16 $M_{\oplus}$	NOM	CMHB	36,461	9×10^9
CSD 3e4 15	0.07 $M_{\oplus}$	NOM	CMHB	17,950	4×10^9

Notes: M_{disk} is the integral mass over all size bins. CMHB=Constant Mass per Heliocentric Bin ($\beta = -1$); DMHB=Constant Mass per Heliocentric Bin ($\beta = -2$). NOM=Nominal mass dependence per size bin ($\alpha = -11/3$); CM=Constant Mass per size bin ($\alpha = -4$).

Figure Captions

Figure 1: Schematic depiction of the Kuiper Disk and the orbits of the outer planets, including Pluto. The clearing between the orbit of Neptune and the inner edge of the present-day disk is created by the dynamical perturbations of the giant planets. The location of the outer boundary of the Kuiper Disk is not well constrained, and may well extend much farther than shown.

Figure 2: Contours of Kuiper Disk collision timescales (in years) as a function of target and impactor size for the model run with a mass per heliocentric bin that declines like R^{-1} , and a “Nominal” population size structure (cf., Table 2). Notice, for example, that large objects are rarely struck by impactors greater than a few kilometers in radius.

Figure 3: Contours of Kuiper Disk collision timescales (in years) as a function of target and impactor size for the model run with a mass per heliocentric bin that declines like R^{-1} , and constant mass (CM) per bin population size structure (cf., Table 2). Again notice that large objects are rarely struck by impactors greater than a few kilometers in radius.

Figure 4: Estimated quasi-steady-state radial optical depths of debris in the Kuiper Disk, as a function of $\langle e \rangle$. Panel *a* corresponds to the collision rate computation shown in Figure 2; recall that the population size structure used in this case extended down to objects with radii of 0.1 km. Panel *b* corresponds to the similar collision rate case that generated Figure 3. In each panel, the bold line corresponds to debris production from strong (i.e., ice/rock) targets; the dashed line corresponds to debris production assuming the targets are mechanically weak (i.e., snow-like). Panel *c* shows a similar calculation, based on the final run case described in Table 2, which has the population size structure sharply truncated for sizes below 1 km. The calculations in all panels assume $v_{ej} = 0.20v_{imp}$.

Figure 5: Estimated thermal emission brightness for a quasi-steady-state debris optical depths of $\tau = 3 \times 10^{-6}$ (panel *a*) and $\tau = 3 \times 10^{-7}$ (panel *b*), assuming $T_{debris} = 40$ K, 50 K, and 60 K. Superimposed are the IRAS, ISO/ISOPHOT, and SIRTf sky brightness sensitivity limits.

Figure 6: The estimated number of detectable collision clouds for the collision rate data presented in Figure 2, assuming a background optical depth of $\tau = 10^{-6}$, and a cloud:sky contrast ratio of $\zeta = 10:1$. The results in panel *a* assume $v_{ej} = 0.20v_{imp}$; the results in panel *b* assume $v_{ej} = 0.05v_{imp}$.

Figure 7: The estimated number of detectable collision clouds for the collision rate data presented in Figure 3, assuming a background optical depth of $\tau=10^{-6}$, and a cloud:sky contrast ratio of $\zeta =10:1$. In panel *a* we assume $v_{cj} = 0.20v_{imp}$; in panel *b* we assume $v_{cj} = 0.05v_{imp}$.























